

Modelling of lake level under climate change conditions: Lake Purrumbete in southeastern Australia

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Abstract Lake Purrumbete is located in western Victoria, Australia, and is highly regarded for its ecological, social, economic and scientific values. Recently, many lakes in the region have been dry or at their lowest level in recorded history, due to a drought that broke in 2010. For this study, a modified difference water budget method was employed to estimate net groundwater flux through the difference between the level of the lake and the water table, along with the specific yield and area of the aquifer. This model successfully modelled the lake level fluctuations. In recent years, Lake Purrumbete has fallen below the outflow level; however, because of its large volume, changes in salinity to date are minor and do not affect its freshwater status. An understanding of how these systems will behave in the future and how they may be best managed in a drying climate is considered an important step to adapt to climate change. Postulated future climatic changes in the region of the lake were used to project the lake level fluctuations to 2030 using the water budget model, and showed that dry conditions would cause the lake level to remain below its outlet elevation, but wet conditions would result in a significant recovery in the lake level. If the level of Lake Purrumbete continues to fall, the main threat to its

ecological status will be the potential loss of some significant areas of fringing wetland habitat. The lowering in lake level could cause a shift in the abundance of algal plankton and so influence the whole lake food web. This may reduce the invertebrate diversity of the lake.

Keywords Deep/fresh lake · Lake Purrumbete · Ecology · Climate change · Australia

Introduction

The interaction between lakes and groundwater systems has been studied both with models and in empirical field studies (e.g. Anderson and Cheng 1993; Lee and Swancar 1997; Genereux and Bandopadhyay 2001; Winter et al. 2003; Nakayama and Watanabe 2008; Roninggen and Burbey 2012). In many closed lakes, groundwater flow often plays a significant role in the net water budget and in the external input of dissolved substances (Hood et al. 2006; Nakayama and Watanabe 2008; Stets et al. 2010).

The western Victorian lakes (Australia) have long been the focus of scientific and conservation work, because of the important ecological communities they support. Many of the lakes show significant signs of stress due to extended drought and climate change.

Lake Purrumbete, in particular, is recognized for its economic value as one of the few freshwater lakes in a region of predominantly saline and hypersaline lakes. The significance of this lake is recognized in the Corangamite local government planning scheme, and there is great interest from the wider community to quantify the effect of future climate change on both the lake water level and quality. Even small changes in the hydrological budget of the western Victorian lakes are reflected rapidly and

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directly by physio-chemical and biological events, such as an increase in salinity and changes in food webs (Williams 2002; Timms 2005). Therefore, Lake Purrumbete offers a unique opportunity to quantify the effects and mechanisms of climate change (Jones et al. 2001; Williamson et al. 2009). Lake Purrumbete was chosen because it has a good historical lake level record, which can be used to validate hydrological models, and represents a deep freshwater lake in the region.

Recent marked declines in rainfall across southern Australia are in general agreement with the predictions made by the CSIRO's Global Climate Models (GCM) evaluation (CSIRO 2001). Many lakes in the region became dry or reached their lowest level in recorded history during the recent drought (1997–2010); therefore, there is a need to develop an understanding of the sensitivity and resilience of lakes to prolonged drought and/or climate change. An understanding of how these systems will behave in the future and how they may be best managed in a drying climate is considered an important step in climate change adaptation. A number of studies have focused on the influence of climate on lakes elsewhere in the world (e.g. Yao et al. 2009) and in this region (western Victoria), including paleoclimatic history of some lakes (Bowler 1981; Gell et al. 1994) as well as climate and lake level modelling (De Deckker and Williams 1988; Jones et al. 2001; Kirono et al. 2012). Timms (2005) considered some of the likely impacts of anthropogenic climate changes on the western Victorian lakes. These impacts include shifts in ecological character, reduced biodiversity, shrinking lake area, increased ultraviolet light impacts and changes in pH.

Lake Purrumbete has been previously examined as part of several studies in western Victoria on different aspects of lake hydrology. Turnbull (2006), Barton et al. (2007) and Cox et al. (2007) distinguished recharge from throughflow and discharge lakes in the region using stable isotopes (d^2H and $d^{18}O$) and Cl/Br ratios; 8 of the 28 lakes investigated (including Lake Purrumbete) were throughflow lakes. Tweed et al. (2009) assessed the impacts of the 1997–2010 drought on the same 28 lakes (including Lake Purrumbete) by integrating satellite remote sensing with on-ground field monitoring data. The 28 lakes decreased in surface area by 60 % on average, and 36 % of the lakes showed groundwater–lake hydraulic gradient reversals, changing from throughflow or discharge to intermittent recharge lakes. The increased salinization observed during the drought caused a 25 % increase in the number of lakes with evaporite deposits. This study also highlighted the spatial variability of the rate of change for different lakes within the catchment. Sources of some of this variability include surface inflow diversions, excessive groundwater extraction and climate change (Leahy et al. 2010; Tibby et al. 2012; Kirono et al. 2012). Timms (1976) provided

some information on the hydrology of Lake Purrumbete as part of a detailed limnological study, and Tibby and Tiller (2007) studied the climate-water quality relationships in Lake Purrumbete for a limited period (1983–2000).

Kirono et al. (2012) studied the likely impact of future climate change on lake level for three maar lakes located in western Victoria, by projecting lake level changes to 2100, assuming that the climate of the last 10 years (1998–2008) continued into the future. The results of the modelling by Kirono et al. (2012) suggest that all lake levels will continue to fall. Coram (1996) and Jones et al. (2001) studied the hydrology of a number of lakes within a 60 km radius of Lake Purrumbete (but not Lake Purrumbete itself). They found that precipitation and evaporation were the dominant influence on historical lake levels, so that a fall in lake water level was initiated by a decrease in the precipitation/evaporation ratio. A perched water table helped some of the lakes maintain high lake levels, despite the recent climate change. Given the prospect of future climate change, changes such as in rainfall, evaporation, surface inflow/outflow and groundwater inflow/outflow may adversely affect most of the crater lakes (including Lake Purrumbete) in the region.

An understanding of how these systems will behave in the future and how they may be best managed in a drying climate is considered an important step to adapt to climate change, and future strategies need to consider the full impact of climate and anthropogenic change on the regional water resources and associated ecosystems (e.g. Milly et al. 2008). At present, there have been no published models that enable the prediction of future changes to freshwater lakes such as Lake Purrumbete in the region (except for the saline lakes by Kirono et al. 2012) due to climate change. This study presents the first of such models, whereby future climate change scenarios of some climatic variables are generated and then fed into the spreadsheet lake water balance model of Yihdego and Webb (2014). The objectives of the study are to predict the future climatic conditions of the Lake Purrumbete region up to 2030, using GCM data, and to identify implications for future management. The paper highlights the potential changes to drivers of ecological communities resulting from climate change and their effect on the Lake Purrumbete water balance, and has the potential to raise awareness and argue for water sustainability, ecosystem health and conservation of small, low salinity and deep lakes in southeastern Australia and elsewhere.

Regional setting

Lake Purrumbete lies within the Corangamite catchment, located ~100 km west of Melbourne in southeastern

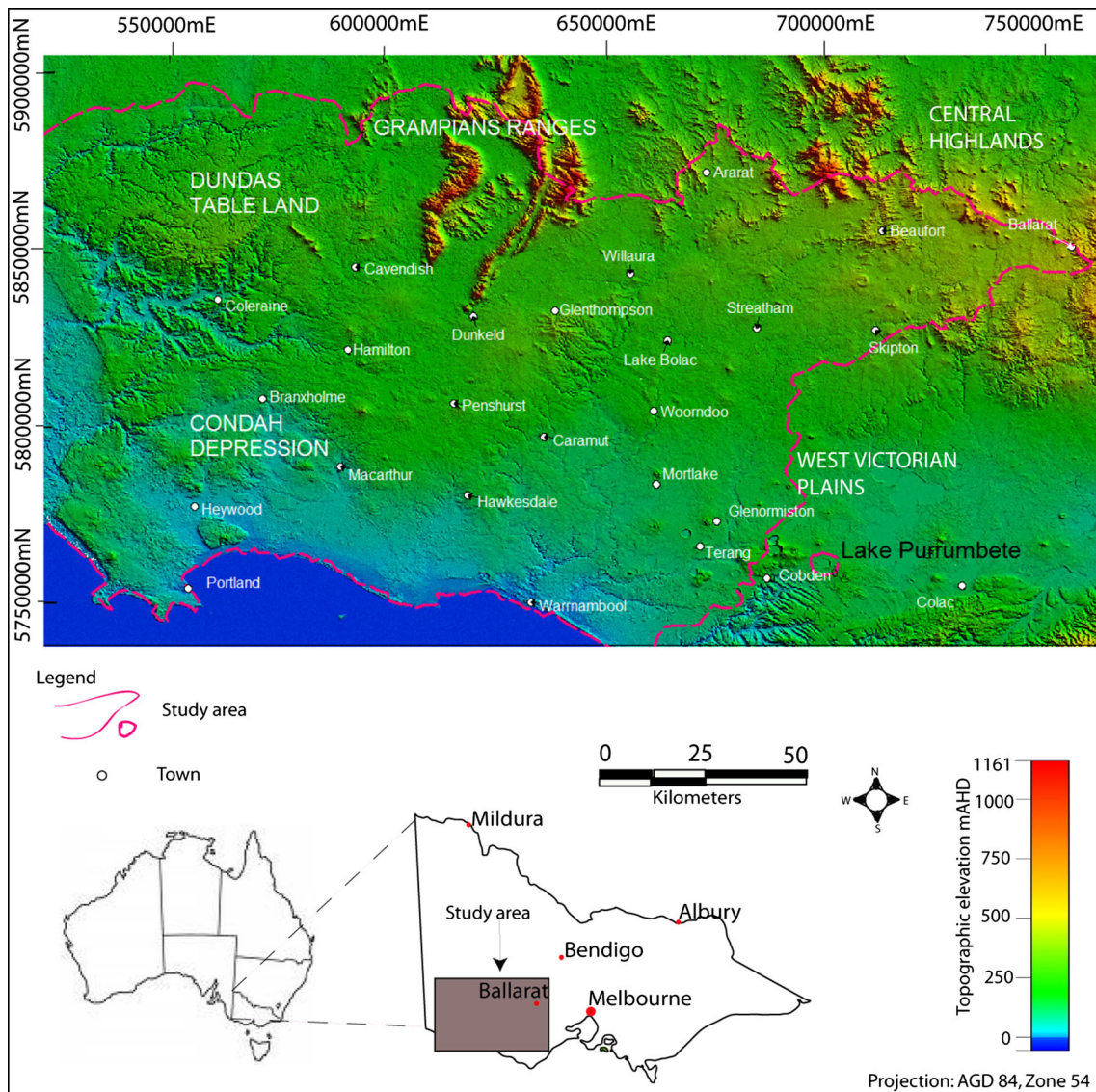


Fig. 1 Study area location, major towns, geomorphic units and major topographic features

Australia (Fig. 1). The climate in the region is temperate, characterized by mild to hot summers and cool, wet winters. Average maximum temperatures during summer range from 22 to 25 °C and from 11 to 13 °C during winter. Evaporation exceeds precipitation except from June to September. Average annual rainfall at Cobden, ~13 km southwest of Lake Purrumbete, is 839 mm, and average annual evaporation exceeds 1,000 mm.

In western Victoria, Australia, there are many volcanic crater lakes, including Lake Purrumbete, which were formed by explosive maar eruptions. These lakes are highly regarded for their recreational, economic, social, ecological, conservation and scientific values. Many of the lakes have supported significant populations of migratory bird species and a number of threatened plant species. Their

value saw the creation of a Western Lakes Ramsar (The Convention on Wetlands of International Importance, especially as Waterfowl Habitat) site, designated nationally and internationally as significant wetlands. Australia has obligations for their protection under “the Ramsar convention” (Leahy et al. 2010).

Lake Purrumbete is located near the southeastern margin of an extensive, gently undulating plain occupying much of southwestern Victoria, which is composed of Plio–Pleistocene basaltic lava flows (Newer Volcanics) erupted from ~400 scattered scoria cones and lava shields (Fig. 2; Joyce et al. 2003). The basalts are 10–130 m thick and form a major unconfined to semi-confined regional aquifer system (Fig. 3). The older flows (1–6 Ma) are generally covered by thick, clay-rich soils up to 10 m thick.

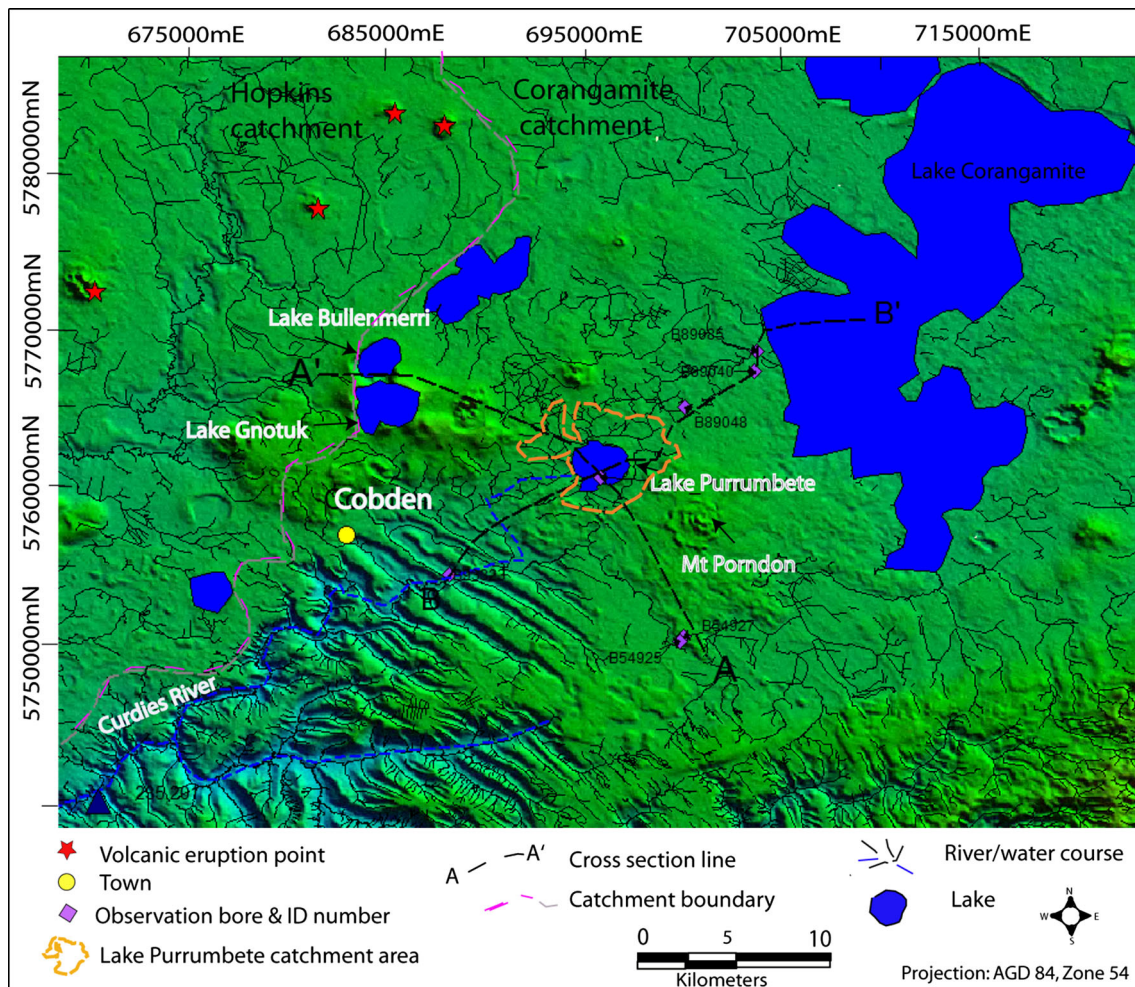


Fig. 2 Location map of Lake Purrumbete area

The original vegetation covering much of the basalt plains has been extensively cleared for agriculture. The more recent basalts (300,000–8,000 years old) are dominated by rocky outcrops with little soil development (“stony rises”), and are often covered with native eucalypt woodland. Concentrated along the southern edge of the volcanic plains are ~40 maars, volcanic craters, each surrounded by a ring of volcanic ash deposits and formed by explosive eruptions that probably occurred in the Late Pleistocene.

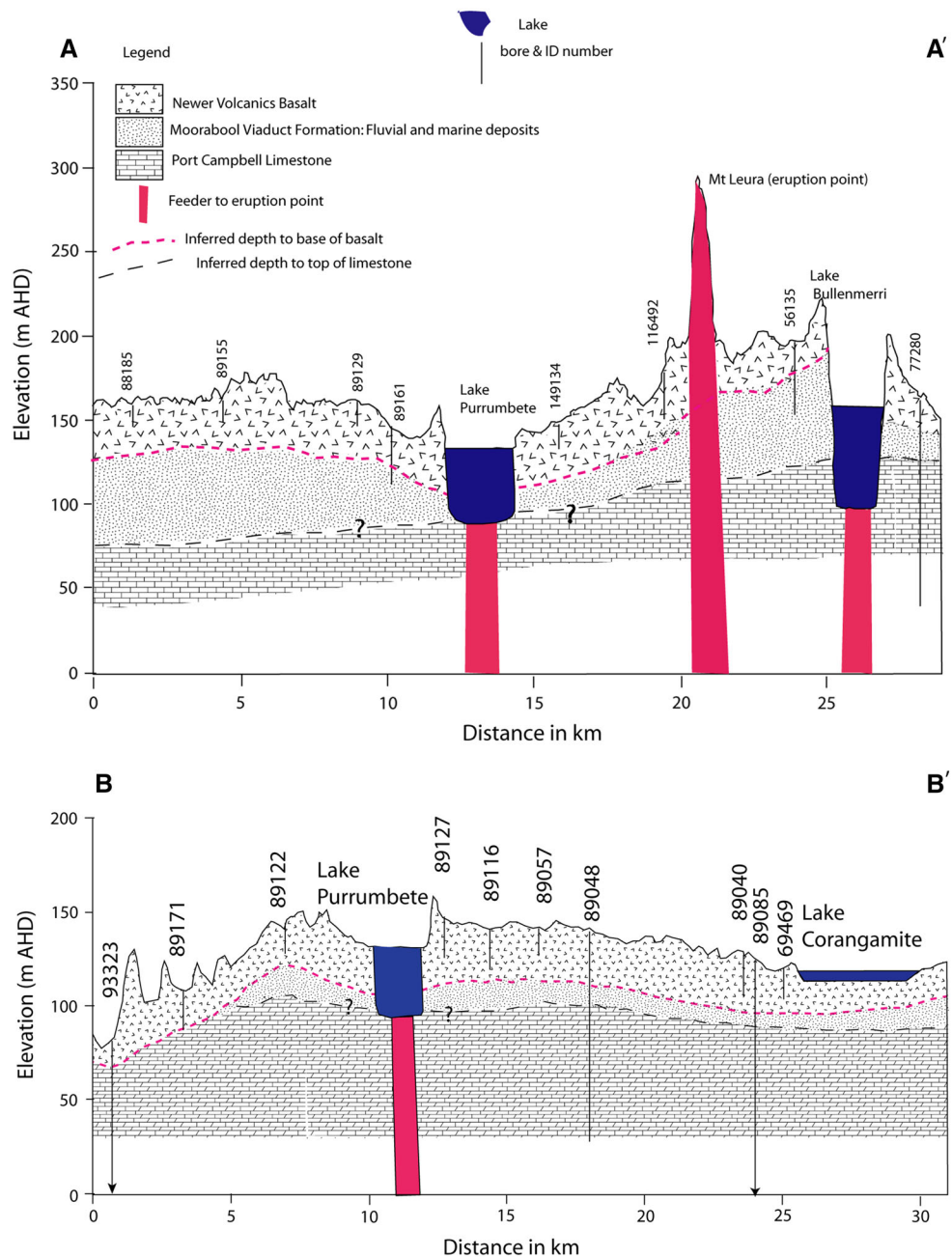
The basalts overlie the Upper Miocene to Pliocene Moorabool Viaduct/Loxton Formation (formerly called Dorodong Sand and Moorabool Viaduct Formation in this area), which comprises marine and fluvial quartz-rich sands and clayey sands usually <10 m thick (Paine et al. 2004). Beneath the Moorabool Viaduct/Loxton Sand are the Upper Eocene to Oligocene Port Campbell Limestone and underlying Gellibrand Marl (Fig. 3). The limestone is composed of dominantly sand-sized bioclastic grains with a high intergranular porosity (~40 %) and permeability

(150–400 m²/day); it forms a major regional aquifer underlain by the aquiclude of the Gellibrand Marl (Edwards et al. 1996; Jones et al. 2001; Shugg 1988).

Approximately, 6 km to the southeast of Lake Purrumbete is the volcanic dome of Mount Porndon (Fig. 2). This is surrounded by basalt lava flows forming an area of ‘stony rises’ (Fig. 4), which have thin rocky soils and are often covered by native vegetation. The stony rises extend around the eastern and southern sides of Lake Purrumbete. The explosive eruption that formed the Lake Purrumbete maar (Fig. 3) occurred through these earlier basalt flows, which are now buried by tuff around the crater rim (Currey 1970; Ollier 1968).

Nested piezometers within the Corangamite region screened across the Moorabool Viaduct/Loxton Formation and the Newer Volcanics show identical reduced water levels (data from VWDW 2010), suggesting a very good hydraulic connection between the two units (Cox et al. 2007). The estimated hydraulic conductivity of the Moorabool Viaduct/Loxton Formation and the Newer

Fig. 3 Geological cross sections showing aquifers that interact with Lake Purrumbete; for locations see Fig. 2



Volcanics are similar: 10^{-2} – 10^1 m/d and 10^{-3} – 10^2 m/d, respectively (Dahlhaus et al. 2002). Thus, there is no reason to separate these units hydrogeologically (Cox et al. 2007).

The area has a poorly developed surface water drainage network, with over 1,500 widely dispersed wetlands and lakes, many of which drain internally. In general, they are small, shallow (average: 0.5–6 m), ungauged and on private property. Lake areas range from only 0.13 to 241 km². There are three crater lakes, Lakes Purrumbete, Gnotuk and Bullenmerri, which are relatively deep (15–66 m) (Williams 1981; De Deckker and Williams 1988). The lake

water salinity levels in lakes in the region range from fresh (<0.5 mS/cm) to brines (>400 mS/cm) (Leahy et al. 2010; Barton et al. 2013).

Generalized water balance modelling of lakes on the volcanic plain, including the integration of satellite imagery with monitoring data, found that for over 30 lakes in the region (including Lake Purrumbete), climatic factors (precipitation and evaporation) are the dominant influences on lake level, area and salinity, with concomitant impacts on groundwater–lake interactions (Jones et al. 2001; Tibby and Tiller 2007; Tweed et al. 2009; Dewi et al. 2009; Kirono et al. 2012). The groundwater component of the

Fig. 4 Satellite imagery of Lake Purrumbete (Imagery courtesy of Google Earth)



lake water balances (in those studies which considered groundwater) was quantified by the difference method, but Barton et al. (2007) and Cox et al. (2007) used stable isotopes and Cl/Br ratios to determine groundwater input for 28 lakes and found that 8 of them (including Lake Purrumbete) were groundwater throughflow lakes.

Lake Purrumbete

Lake Purrumbete is a volcanic maar lake (Fig. 3). It covers an area of 5.52 km² (Fig. 2) and is surrounded by a wide circle of phreatomagmatic deposits forming a tuff ring (Ollier 1968), with the highest points along a ridge on the eastern side (Fig. 3). The maar was formed by an explosive single-point eruption (Hills 1940; Ollier 1968). Lake Purrumbete has a catchment area of ~30 km² (Fig. 2). The lake is a popular trout fishing spot and is a wildlife sanctuary. Lake Purrumbete is protected through the Victorian park and reserve system (natural conservation reserves/wild life reserves).

The lake is fed by natural and artificial drainage channels which flow from the north and northeast into its northern and eastern sides, respectively (Figs. 2, 4). The lake outlet, which was dug through a low rock ridge, is situated on the southwest shore of the lake, flowing into Curdies River (Figs. 2, 4). The outlet was constructed to drain the low swampy areas to the south and southeast of the lake (Fig. 4), so they could become agricultural land. The base of the outlet has been deepened several times, from 134.99 m Australian Height Datum (AHD) before

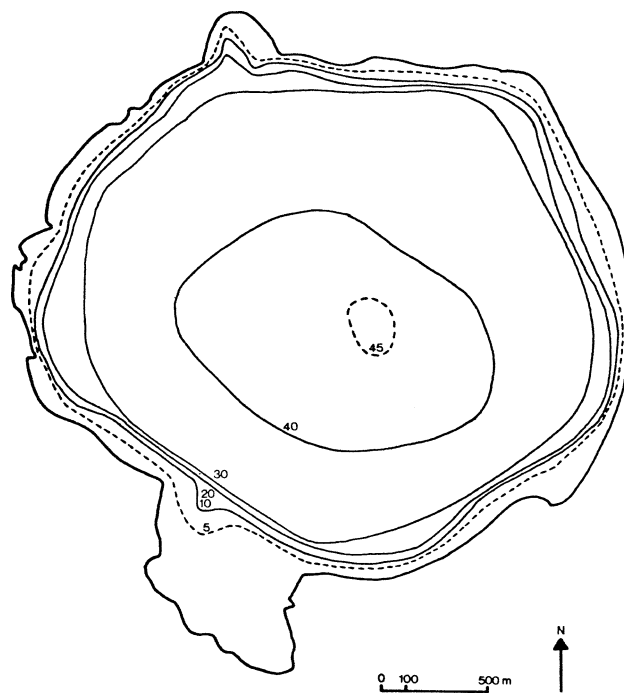


Fig. 5 Bathymetric map of Lake Purrumbete (after Timms 1973). Isobath intervals at 10 m

1981, to 134.79 m AHD in 1981 and 134.6 m AHD in 1992.

The bathymetry map of Lake Purrumbete (Fig. 5) shows two sub-lacustrine channels on the northwest and southwest sides of the lake, probably formed by sub-aerial processes and later flooding (Hutchinson 1957). Lake

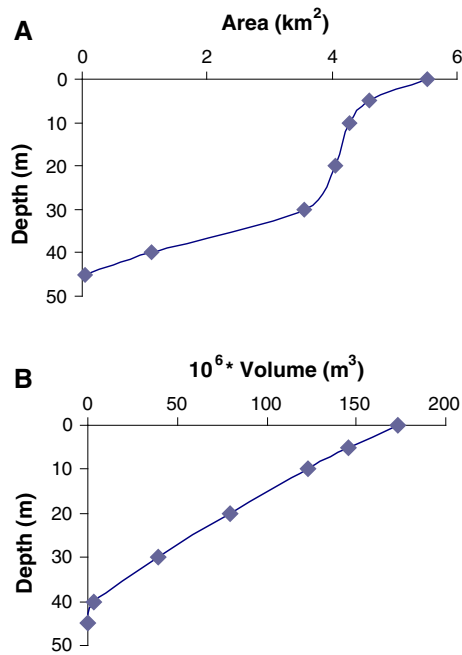


Fig. 6 Cumulative hypsographic curve (a) and volume curve (b) for Lake Purrumbete based on bathymetry

Purrumbete is the only local maar lake known to spread beyond the rim of its crater and to have sub-lacustrine channels. The other local maar lakes for which bathymetric maps exist (Lake Bullenmerri (Timms 1976), Lake Gnotuk (Hussainy 1969), the Mt Gambier lakes (Tamuly 1969; Timms 1974) and the Basin lakes (Timms and brand 1973)) are all confined to their craters and receive water by seepage and sheet runoff. The crater rims around these lakes provide differing degrees of wind protection; Lake Purrumbete is the most exposed (Timms 1976). The crater rims are low and wide, but the nature of the crater rim varies (Figs. 5, 6). In Lake Purrumbete it is almost all pyroclastic (Ollier 1968), while in other lakes there are outcrops of country rock (Currey 1970).

Lake Purrumbete is a deep lake, with a maximum depth of 45.7 m (Gregory 1903; Ollier and Joyce 1964) and is exceeded by only a few others on the Australian mainland (e.g. Blue Lake at Mount Gambier, which is ~77 m deep; Tamuly 1969).

Lake Purrumbete is fresh (median 460 mg/l). Detailed electrical conductivity (EC) measurements for the year 1965/66 (Hussainy 1969) showed that the lake total dissolved solids (TDS) fluctuates by only about 15 mg/l annually.

Historical trends

Lake Purrumbete is currently fresh (median 460 mg/l), and has been recorded as fresh since European settlement

in the 1830s (Timms 1976; Williams 1981). Monthly lake level and salinity data are available for Lake Purrumbete from 1978 to 2009 and 1982 to 2009, respectively. Lake level measurements are not available from 1994 to 1997. Both rainfall and evaporation data are available from the Bureau of Meteorology (BOM 2010). Stream flow data are available from the Victorian water resources data warehouse (VVDW 2010).

The relationship between the level at Lake Purrumbete and precipitation (rainfall total) from Cobden station located west of Lake Purrumbete (Fig. 2), between 1978 and 2006, is displayed in Fig. 7. This indicates that water levels in the lake are influenced by short-term variation in annual rainfall, except for a period between 1990 and 1994. However, the sustained decrease in rainfall that occurred after 1997 affected lake levels in Lake Purrumbete, which fell by over a metre. In August 2007 the water level was about 0.5 m below the base of the outflow channel at 134.6 m. Figure 7 shows a strong correlation of cumulative deviation of rainfall from the annual mean for Cobden with lake levels; peaks in the lake level generally correspond to periods of above average rainfall. In years of below average rainfall, the lake level declines, as occurred in 1983 and 2000 (Fig. 7). Similarly, groundwater level in the region is sensitive to climatic variability (Dahlhaus et al. 2010; Yihdego and Webb 2011).

There has been no large increase in the salinity of Lake Purrumbete since the lower rainfall began in 1997 (Fig. 8) and detailed electrical conductivity (EC) measurements for the year 1965/66 (Hussainy 1969) showed that the lake total dissolved solids (TDS) fluctuates by only about 15 mg/l annually. Salinity values in Lake Purrumbete recorded between 1982 and 2006 were all below 2,000 mg/l (Fig. 8) peaks in the 1980s and 1990s could be an effect of other (natural) causes.

Long-term rainfall

Annual rainfall in the Corangamite catchment (Fig. 2) ranges from 600 to 1,000 mm (Fig. 9a). Long-term rainfall trends for the study area, plotted as cumulative residual rainfall curves (cumulative deviation from monthly average rainfall), show distinct phases (Fig. 9b) including a pre-1945 below average or drought-dominated period (downward slope), a 1945–1970s period with wetter than average (flood-dominated) conditions (upward slope) and a post-1997 period of drought. These trends are also captured in long-term stream flow records in the Murray–Darling Basin north of the study area (Jones et al. 2001). In general, Australia has become wetter since 1900, owing to an increase in rainfall intensity and number of rainfall days in all months except winter (Suppiah et al. 2007).

Fig. 7 Lake level with variation in rainfall

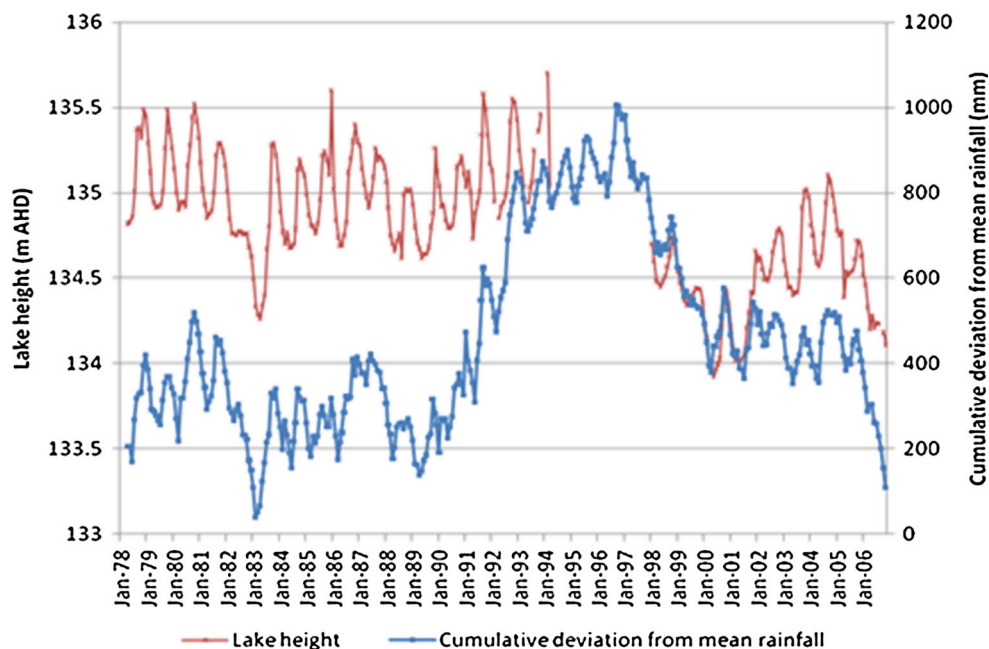
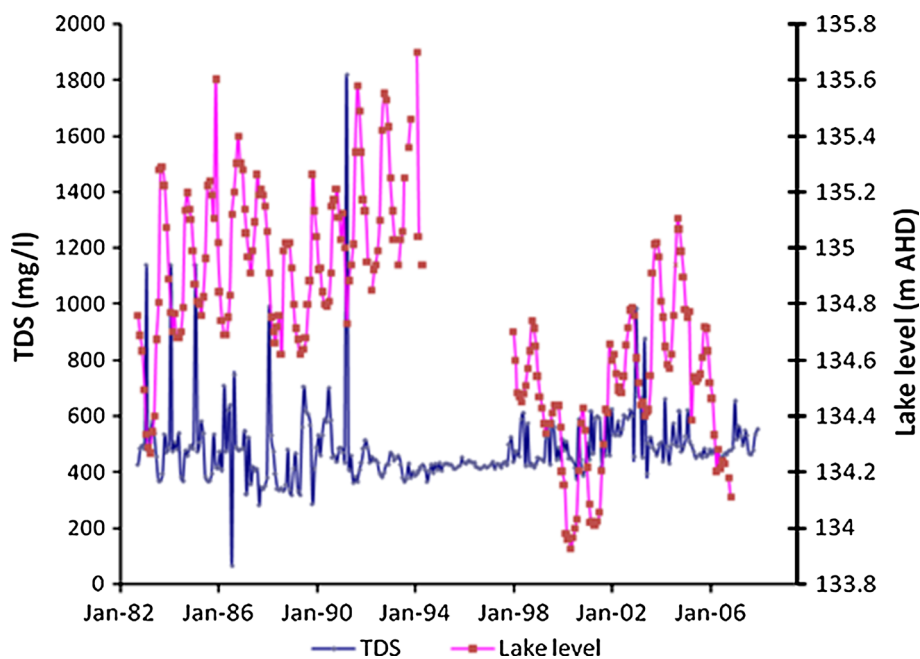


Fig. 8 Relationship between measured lake depth and TDS for the period 1982–2007



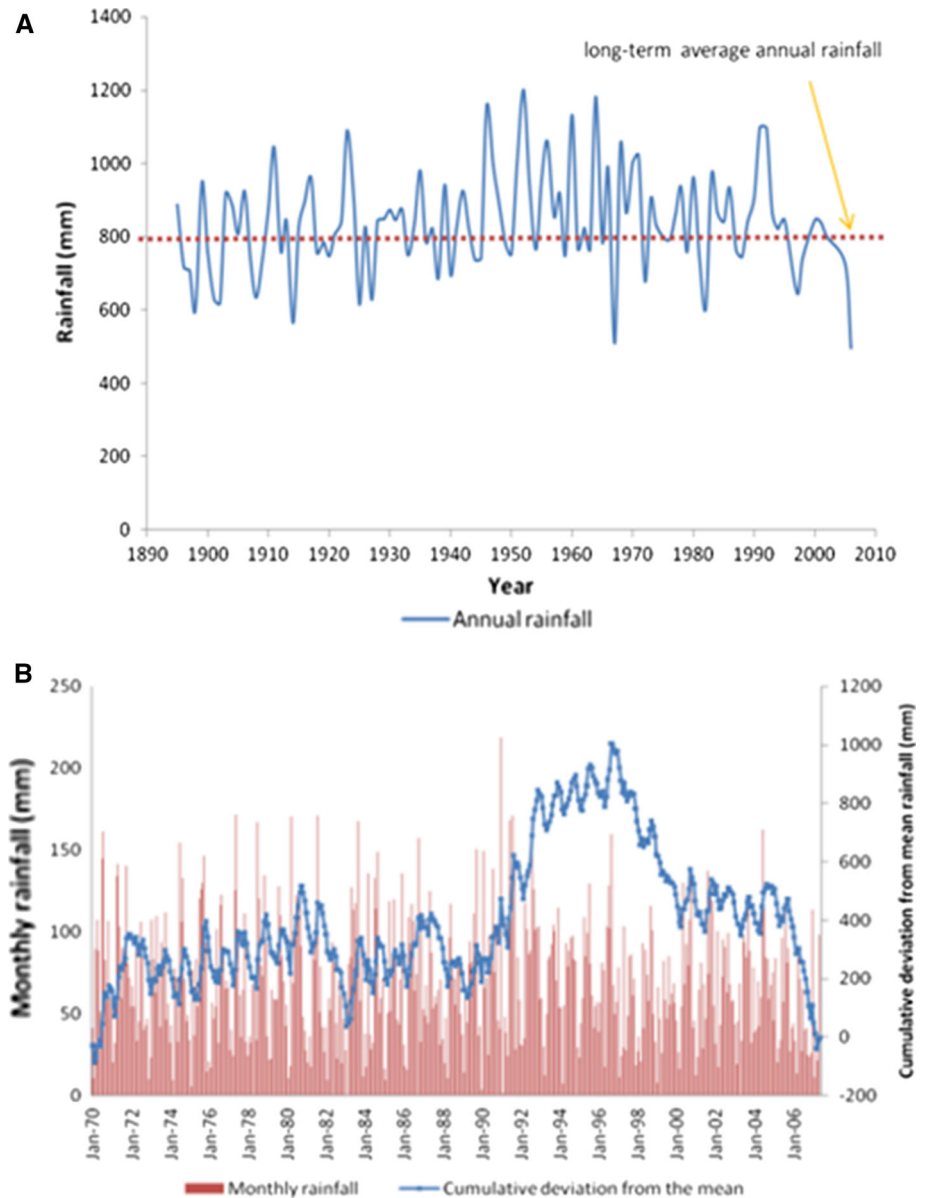
A comparison of cumulative residual rainfall plots across the study area (Fig. 9b) shows that although there is some variation, trends over the 1996–2007 period generally show strong negative slopes representing a long period of drought.

Future climate projections

The influence of anthropogenic warming on climate conditions in southern Australia is uncertain. It is highly likely

that warmer conditions can be expected, but there is considerable uncertainty about the magnitude of warming and how rainfall patterns will be affected, particularly at the catchment and sub-annual scale. Even in the absence of human-induced climate change, Australia's climate is not stationary, but is influenced by naturally occurring climate phenomena that operate over periods of years to decades. The most dominant of these in eastern Australia is the El Niño/southern oscillation (ENSO) and the interdecadal Pacific oscillation (IPO), although recent research indicates

Fig. 9 **a** Rainfall at Cobden, **b** with its cumulative deviation from the mean



that the southern annular mode (SAM) also plays a significant role for at least the southern third of Australia (Franks 2004). The ENSO cycle operates over periods of 2–5 years, and its extremes are characterized by warmer and drier El Nino events and cooler and wetter La Nina episodes. The IPO operates over longer time periods of two to five decades in either a drier (IPO positive) or wetter (IPO negative) phase.

Recent climate modelling predicted that by 2050, droughts will become more frequent and the number of drought months will increase by up to 20 % over much of the Australian continent (CSIRO 2001; Mpelasoka et al. 2008). The predicted increases of average annual temperature are 0.2–1.4 °C by 2030 and 0.7–4.3 °C by 2070 for southern Victoria (Suppiah et al. 2007), accompanied by a

projected increase in potential evaporation (Hughes 2003) and a decrease in winter rainfall by up to 8 % (Whetton et al. 2005).

The modelling of future rainfall regimes predicts a likely decrease of –9 % to an increase of +3 % by 2030, and –25 to +9 % in 2070 for the southern part of Victoria (Suppiah et al. 2004). This predicted rainfall reduction is primarily caused by a reduction of winter rainfall, although some models show increased summer rainfall (Shi et al. 2008). Median data from 14 global climate models (GCM) used by the Intergovernmental Panel on Climate Change (IPCC) show a considerable predicted increase in evaporation and decrease in precipitation in the study area (Leahy et al. 2010). A predicted one degree rise in temperature by 2030 will cause significant changes in monthly

Table 1 Changes in precipitation, evaporation and runoff at Lake Purrumbete assuming a one degree rise in global temperature by 2030 (average of 14 global climatic models; modelling by CSIRO 2001)

Month	Precipitation (%)	Evaporation (%)	Runoff (%)
January	−4.4	4.0	−10.72
February	−0.3	2.8	−10.72
March	−2.5	3.4	−8.07
April	−2.0	4.1	−8.07
May	−4.5	5.3	−8.07
June	−4.6	6.8	−9.64
July	−3.4	4.4	−9.64
August	−2.3	4.3	−9.64
September	−5.2	3.7	−12.57
October	−6.2	3.7	−12.57
November	−6.6	3.2	−12.57
December	−8.5	3.2	−10.72

precipitation, evaporation and runoff at Lake Purrumbete (Leahy et al. 2010).

The Environment Protection Authority (EPA) Victoria engaged CSIRO Marine and Atmospheric Research to rework the IPCC (2007) global climate models (GCMs), to provide projections of climate change effects on precipitation, runoff and lake evaporation for Lake Purrumbete (Table 1). The projected change in precipitation was estimated using the ‘pattern scaling’ approach of Whetton et al. (2005). Projected changes in lake evaporation were calculated using Morton’s lake evaporation model (Morton 1983), whereas runoff was calculated using the method of Preston and Jones (2008).

This information (Table 1) was used in water balance modelling described below.

Assessment of the likely impact of future climate change on Lake Purrumbete

A spreadsheet water balance model developed by Yihdego and Webb (2014) was used to examine the impact of the projected climate change by 2030 on Lake Purrumbete lake level. The spreadsheet model (Yihdego and Webb 2014) used in this study has the capability to simultaneously solve the conservative solute mass balance along with the water mass balance of the lake, providing additional constraints on the water balance. Conservative solutes have been successfully used to constrain the water balance of lakes in a number of cases (e.g. François and Philippe 2004; Fuhrihan and Merrit 1981; Yadav and Keshari 2007).

The spreadsheet model employs a new modified difference water budget method that improves the groundwater flux estimate using only Darcy’s law by linking the lake to

the groundwater and incorporating the seasonal variation of the groundwater fluxes, thereby including seasonal changes to the hydrogeological and meteorological conditions within the lake catchment. Both the observed climate data and climate scenarios were applied to the lake water balance model of Yihdego and Webb (2014) to estimate the future lake level. Yihdego and Webb (2014) have demonstrated that this lake balance reproduces the seasonal/decadal and historical rates of decline in lake level of lakes in the region. For details of the model the reader is referred to Yihdego and Webb (2014).

The model was reworked to predict lake levels based on projected climate change by 2030 (Table 1). On top of the projections from climate change, two base climate periods of 10 years each were examined: the wetter period between 1985 and 1995, and the drier period between 1997 and 2007. This allowed the impact of climate change to be examined under both wetter and drier condition.

Bathymetry data are available for Lake Purrumbete (Fig. 5; Timms 1973). The relationship between lake area and depth was also established by measuring the lake area on 12 Landsat images taken between 1972 and 2004 and plotting this against the measured lake depth in the month when the images were taken. The two relationships are comparable, and the depth–area–volume relationship (Fig. 6) was built into the model using the bathymetry data.

The model for water volume in the lake was run on a monthly basis for the period 1978–2010. It incorporated precipitation, evaporation, surface inflow, surface outflow, water extraction for irrigation, stock and domestic use, groundwater inflow and groundwater outflow. For the modelling, the initial volume in April 1978 was calculated from the measured water depth in that month (134.82 m).

Precipitation and surface water inflow to the lake

The model used monthly precipitation data from the weather station at Cobden (Fig. 2), about 13 km southwest of Lake Purrumbete, where the average rainfall is ~800 mm (Fig. 8a). It is the nearest weather station with a long-term and continuous record extending to the present. The Cobden station has approximately the same elevation as Lake Purrumbete.

Surface inflow to Lake Purrumbete is estimated by the tanh cumulative surplus rainfall approach (Grayson et al. 1996; Kim et al. 2010; Yihdego and Webb 2013) using the Curdies River flow, which is gauged at Timboon (gauge no. 235201; Fig. 10), because Lake Purrumbete is located in the headwaters of the Curdies River catchment. The tanh cumulative surplus rainfall approach provides a tool from which runoff in the Curdies River can be predicted for any

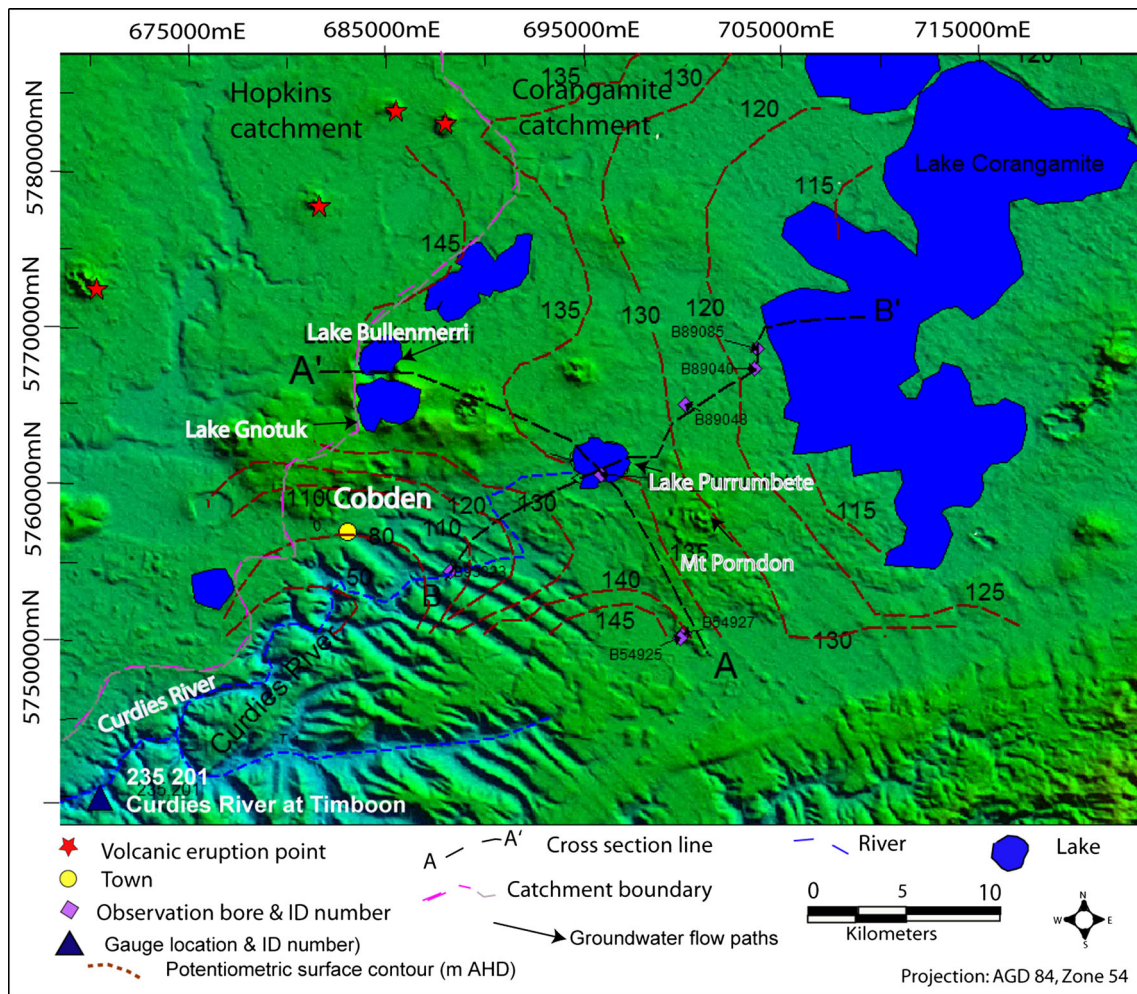


Fig. 10 Potentiometric surface elevation (m AHD) of Lake Purrumbete area (modified after Tweed et al. 2009)

given monthly precipitation/evaporation. Using area scaling, this can be converted to a surface inflow flow to Lake Purrumbete; the catchment areas for Lake Purrumbete and Curdies River at Timboon are 30 and 824 km² respectively.

Water losses from the lake

The model used actual monthly pan evaporation data measured at Hamilton Research Centre from 1965 to 2001. The missing pan evaporation data to the present was added from the measured monthly data for White Swan Reservoir, which is strongly correlated to that at Hamilton. Direct lake evaporation was calculated using a monthly pan evaporation estimate with a pan coefficient of 0.6. A local calibration coefficient (0.95) was used to adjust the pan evaporation data set, taking the difference in elevation, site condition and storage effect between White Swan Reservoir (the measurement site for pan evaporation) and Lake Purrumbete into account.

Surface water outflow was simulated by setting the outflow level at 134.99, 134.79 and 134.6 m AHD for the years of pre-1981, 1982–1991 and post-1992, respectively.

The maximum licenced abstraction volume for domestic, stock and irrigation purposes from Lake Purrumbete is 510 × 10³ m³/year. Although some irrigation licences do not allow extraction when the lake level is below the minimum value of 135.01 m AHD as at 1st November for each irrigation season (SRW 2009), others do not have this clause. Stock and domestic abstraction from the lake does not necessarily require a licence. The amount of water used for stock and domestic uses is unknown.

Groundwater inflow/outflow

Lake Purrumbete intercepts groundwater flow which is recharged through the basalt stony rises and continues through the lake (Fig. 10). Groundwater flows into Lake Purrumbete from the area of stony rises (Fig. 4) to the southeast and away from the lake to the northeast (towards

Lake Corangamite) and southwest (towards Curdies River) (Fig. 10); there is insufficient bore data to definitely determine the groundwater flow direction on the northwest side. Groundwater hydrograph and lake level data indicate there has been no reversal in groundwater–lake hydraulic gradients during the drought, because groundwater levels in all bores dropped at approximately the same rate (Fig. 11).

Lake Purrumbete is hydraulically connected through the side of the lake to the basalt lavas and underlying sand of the Moorabool Viaduct/Loxton Formation; the two formations are grouped as a single hydrogeological unit for the purposes of this model (as discussed previously). Any interaction with the underlying Port Campbell Limestone is likely to be small (Fig. 4). Permeability in the basalt is very variable; an average hydraulic conductivity value of 8 m/day was used based on pumping tests in the area (Cox et al. 2007), and this estimate is in agreement with the average value for the Moorabool Viaduct/Loxton Formation in this region (4.3 m/day; Coram 1996).

For initial estimation of the groundwater inflow using Darcy's Law, the cross-sectional area was calculated by multiplying the lake perimeter of the groundwater inflow zone (1.8 km) by the estimated thickness of the basalt and Moorabool Viaduct/Loxton Formation aquifers intersected by the lake (~40 m). The upflow and downflow hydraulic gradients, calculated from the potentiometric surface map, are on average 0.002. Groundwater outflow was estimated in the same way as groundwater inflow, except the width of the groundwater outflow zone is 6.2 km.

Groundwater discharge/recharge to/from Lake Purrumbete, which has a cylindrical shape, also occurs through the lake bed. A value of 9×10^{-4} m/day (typical of clays) was chosen for the permeability of the clayey lake floor

sediments; this low permeability means that, even though the area of the lake floor is greater than that of the lake margin, the groundwater flux through the lake floor is very small and can be neglected.

However, due to aquifer heterogeneity and a lack of regularly monitored groundwater observation bores in the immediate surrounding of Lake Purrumbete, these calculations were difficult and probably contain large errors, mainly due to uncertainty in values of hydraulic gradient and conductivity, meaning that the groundwater flow system is not well defined. This is important because lake levels rise and decline more quickly than groundwater levels due to direct input from precipitation and open water evaporation, so that hydraulic gradients from groundwater to lake will change seasonally, causing variations in the groundwater flux to the lake. For Lake Purrumbete, groundwater hydrograph and lake level data indicate the hydraulic gradients varied in value but not direction throughout the study period (Fig. 11).

As a result, the initial Darcy's Law estimations were supplemented using a bucket model (Yihdego and Webb 2014) to capture seasonal net groundwater flux. The groundwater inflow and outflow estimates were then optimized during calibration of the model using the calculated net groundwater flux.

Model calibration and sensitivity analysis

Model calibration was carried out by adjusting model input parameters so that the simulated lake levels fit the observed lake levels over the period of time between 1978 and 2007 (which refers to the historic data set), resulting in a monthly average groundwater outflow and inflow of $\sim 70 \times 10^3$ m³ and $\sim 260 \times 10^3$ m³, respectively. The model was calibrated by minimizing the sum of squared differences between observed and simulated lake levels. The models predict the recession in lake levels accurately ($r^2 = 0.84$); discrepancies are mainly due to water abstraction and errors in the over/underestimation of surface inflows, particularly following dry periods (1997–2010). The sum of the squared differences did not exceed 0.09 m². The optimized lake–aquifer conductance is 3.3×10^2 m²/day (i.e. the hydraulic conductivity of the lake shores, which is the aquifer, is ~ 3.6 m/day, comparable with the previous estimate for the basalt and Moorabool Viaduct/Loxton Formation aquifers), while the optimized specific yield and aquifer area are 0.13 and 50 km², respectively. The optimized specific yield (0.13) is comparable with previous specific yield estimates for the basalt aquifer (0.01–0.2) (Dahlhaus et al. 2002; GHD 2004; Cox et al. 2007). The modified method used in this study provided more flexibility to the model to fit the data by increasing the number of parameters.

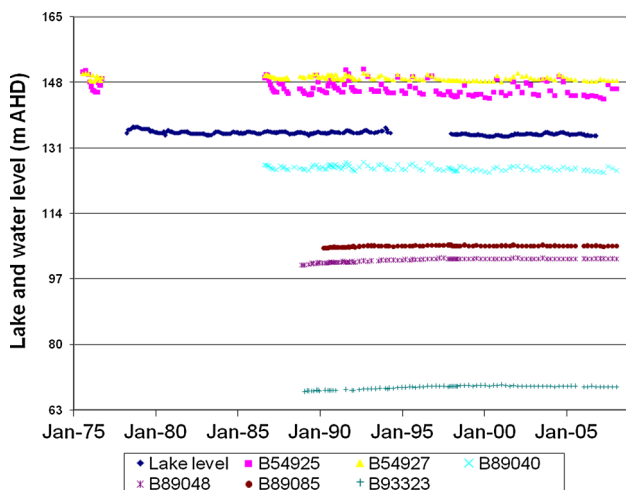


Fig. 11 Groundwater and lake levels (see Fig. 10 for the location of bores)

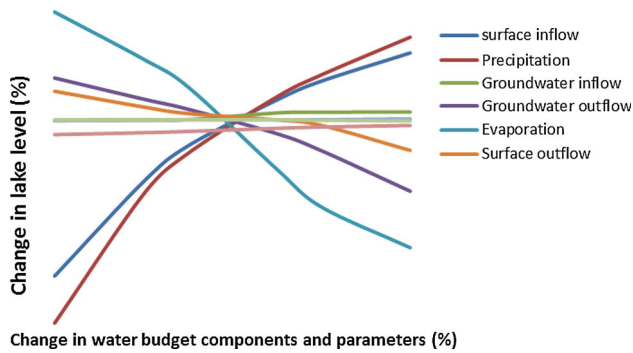


Fig. 12 Relative sensitivity of Lake Purrumbete water balance model to changes in the water budget components

The water balance for the calibrated period of time (1978–2007), shows that the major overall influence on lake levels is evaporation (average ~40 % of the total water budget), followed by direct precipitation (average ~27 %). Surface inflow and outflow account for ~6 and 8 %; groundwater inflow and outflow are 16 and 0.9 %, respectively. Abstraction accounts for ~1.4 %.

Lake Purrumbete was classified by Turnbull (2006) and Barton et al. (2007) as a marginally surface water-dominated, groundwater throughflow lake, based on hydrochemical and isotopic analysis (i.e. high deuterium excess and high bicarbonate/chloride ratio). However, the water budget from the current study shows that direct rainfall and surface water inflow/outflow exceed groundwater flux (~41 and ~18 % of the water budget, respectively). The discrepancy may be partly due to uncertainties associated with the hydrochemical and isotopic data, e.g. the thermal stratification of Lake Purrumbete over summer means that the evaporated surface layer will have different stable isotope and ionic (HCO_3^-/Cl) ratios to the bulk of the lake water.

Sensitivity analysis performed on the input variables (over the same period of time for the model calibration; 1978–2007) showed that the model was most sensitive (lake level) to evaporation and precipitation, and surface inflow to a lesser extent (Fig. 12). There could be errors in surface inflow estimation due to the way it was calculated (as previously discussed), and because the swamps/wetlands (located inside the catchment) that were artificially drained into Lake Purrumbete might have a different runoff ratio to the rest of the catchment.

Model predictions

The predicted water level changes for Lake Purrumbete to 2030 are shown in Figs. 13, 14. The CSIRO projections (CSIRO 2001, CSIRO 2008) for future climatic changes have been taken into account. A predicted one degree rise in temperature by 2030 will cause significant changes in monthly precipitation, evaporation and runoff at Lake

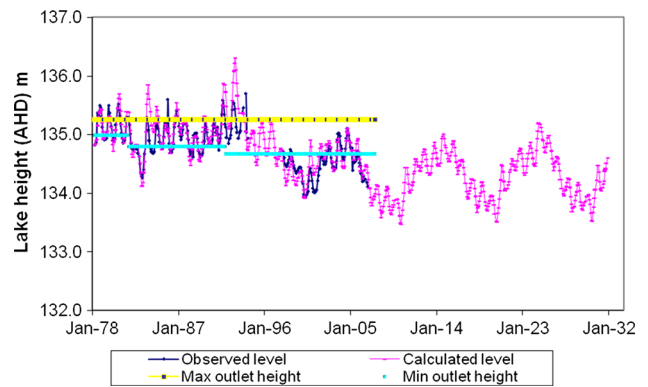


Fig. 13 Scenario 1: simulated lake levels continuing in the dry period (1997–2007) as the climate baseline

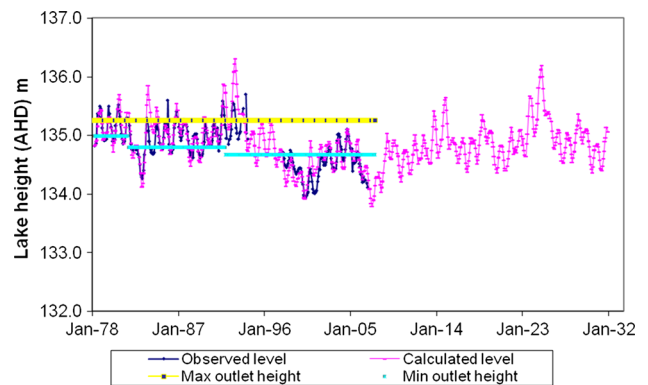


Fig. 14 Scenario 2: simulated lake levels continuing in the wet years (1985–1995) as the climate baseline

Purrumbete (Table 1) using the average output from 14 GCMs, originally generated by CSIRO from a 1990 baseline (an average of 1989–1999). These changes were applied to existing dry (1997–2007) and wet (1985–1995) decadal climate data sets, and the resulting modified climate data sets were repeated to give climate data up until 2030, and then applied to the water budget to model changes in lake level to 2030 (Figs. 13, 14, respectively). In other words, the future climate data series was developed by perturbing the baseline climate baseline data (“wetter” or “drier”) with the GCM time series (i.e. 1997–2030).

The results show that continuing the dry period of 1997–2007 into the future, together with the predicted decreases in rainfall and runoff and increases in evaporation, means that there would be no recovery in the lake level, which would stay below the outflow level (Fig. 13). Clearly, the 16 % of input estimated to come from groundwater is important to the lake in maintaining levels. This is in contrast to the very weak hydraulic connection between Lake Corangamite (largest shallow saline lake in the region) and the surrounding shallow aquifer system, where groundwater input to the lake is relatively minor,

comprising on average 7 % of all inputs, with major inputs being rainfall and surface flows (Tweed et al. 2009).

A study of groundwater interaction of 28 lakes in the region by Tweed et al. (2009) found that many went from being lakes that gain water from the groundwater to lakes that lost water to the groundwater over the very dry period from 1996 to 2005. The very dry conditions over this period depleted the shallow water tables causing them to drop. If this was to happen with Lake Purrumbete, it is likely that lake level in the future will continue to drop, with the earlier predictions of this study (Fig. 13) representing the worst case.

Assuming that the climate returns to the wet conditions of 1985–1995, the model predicts that there would be significant recovery in the lake level, which would rise above the outflow level for most of the time (Fig. 14).

Given the lake's large depth and volume, the relatively small depth changes predicted mean that salinity will change only slightly under the dry climate scenario, and probably not change at all under the wetter climate scenario. The drop in water levels observed until 2008 meant that the large shallow area in the south and south east of the lake (Figs. 4, 5) was no longer permanently inundated. This could have a significant ecological impact, because these areas have sheltered macrophyte beds and may be important nursery areas for fish. Any further drop in lake levels and drying of the areas are likely to have a significant impact on the ecology, rather than any potential change in salinity.

Kirono et al. (2012) projected lake level changes to 2100 for three saline and closed crater/maar lakes (Lakes Keilambete, Gnotuk and Bullenmerri) located in the vicinity of Lake Purrumbete, assuming that the dry climate for the period 1998–2008 continued into the future. Their results suggest that all three lake levels will continue to fall, which is in agreement with the modelling of Lake Purrumbete under a similar climate scenario (Fig. 13). This suggests that a regional plan to manage the quality and amenity of lakes in Western Victoria under a drying climate and other threats is urgently needed (Kirono et al. 2012). The severe impact of the recent drought and the projected predictions made under different scenarios give an indication of the vulnerability of the western Victoria lakes (including deep lakes like Lake Purrumbete) to climatic change and confirm the need to reconsider the full impact of climate change on the regional water resources and associated ecosystems (e.g. Milly et al. 2008).

Discussion and conclusion

A modified difference water budget method for lakes that closely links the lake to the groundwater was able to

successfully model the level fluctuations in Lake Purrumbete, a deep, cylindrical lake located within an extensive basalt plain in western Victoria. Hence, this model can be applied successfully to lakes elsewhere. The modified method used in this study better incorporates seasonal variation and also provides flexibility to fit the data by increasing the number of parameters and processes modelled.

The water model developed for Lake Purrumbete has been calibrated to past climatic conditions (1978–2007) and can be used to predict the effects of future climate changes, but major drawbacks are involved in making these predictions: uncertainty in the calibrated model and uncertainty about future hydrologic changes. The accuracy of predictive simulations is difficult to assess, so it is wise to assume a fair amount of uncertainty (Whetton et al. 2005) when using them for design and management purposes. However, since the drought broke in 2010, it is possible to assess the model's performance in the post-drought conditions. The predicted lake level (scenario 2: assuming the climate returns to wet conditions) matches with the recently observed lake level and hence gives confidence for the application of the model prediction.

The role of groundwater in maintaining lake level

Over recent years, there has been a growing recognition of the importance of evaluating groundwater contribution to lakes (e.g. Kirillin et al. 2013; Yang et al. 2014; Yihdego and Becht 2013; Yihdego and Webb 2012). Conceptual models of groundwater flow into lakes (Zlotnik et al. 2009), based primarily on numerical simulations and near-shore measurements, predict that the majority of groundwater discharge into a lake occurs in the shallow near-shore, littoral zone (Winter 1981; Munter and Anderson 1981; Turner and Townley 2006), with decreased rates of groundwater flow farther from shore (Lee 1977; Lee and Barry 1980). However, as lake size and water depth increase, lakes (like Lake Purrumbete) are more likely to be fed by regional groundwater flow systems and the contribution of groundwater to the deeper regions may therefore be more significant.

In the present modelling, the optimized aquifer area in hydraulic contact with Lake Purrumbete is 50 km², which is greater than the surface catchment area of the lake (30 km²), indicating that the lake interacts with the groundwater beyond the surrounding drainage divide, probably due to its significant depth (45 m).

In line with this, the lake water budget in this study (over the calibrated period of time: 1978–2007) shows that Lake Purrumbete has a volumetrically significant interaction with the surrounding groundwater system (groundwater inflow and outflow altogether account for 16.9 %), due to its significant depth.

The modelling results over the calibrated period of time (1978–2007) show that the lake level fluctuations are primarily driven by the surface water inflows and direct rainfall during wetter months and evaporation during drier periods. Groundwater inflow/outflow accounts for a significant proportion of the Lake Purrumbete water budget, unlike other shallow lakes scattered across the volcanic plain in western Victoria (Coram 1996; Jones et al. 2001; Cartwright et al. 2009; Tweed et al. 2009), for which groundwater plays a minor role in maintaining lake levels compared to rainwater (Jones et al. 2001; Tweed et al. 2009). It would appear, on the basis of the studies available, that groundwater input from the shallow water tables/in the basalt aquifer (Fig. 3), although variable, is on the whole unlikely to maintain these lake levels in a prolonged or sustained drought or under permanent change in climate to drier conditions.

Implications of current and projected climate changes for the conservation status of the lake

Lake Purrumbete has remained in a freshwater state despite the generally drying climate of the last decade, because it is in a wetter part of the region, is very deep, contains a very large volume of water and has maintained an outflow for most of the historical record, meaning that salt has not been able to accumulate in the lake. In recent years Lake Purrumbete has fallen below the outflow level, however, due to its large volume; changes in salinity to date are minor and have not affected its freshwater status. If there is any return to a wetter climate, then Lake Purrumbete will outflow again with no change in salinity status. If the level of Purrumbete continues to fall, the main threat to its ecological status is the potential loss of some significant areas of fringing wetland habitat (Figs. 4, 5). Clearly, the lakes that are currently fresh have a set of conditions that have enabled them to withstand change throughout a prolonged period of dry climate. However, the sharp decrease in rainfall that we have seen since 1997 means that even some of these systems could be in danger. Previous studies have demonstrated that lakes elsewhere (e.g. Yao et al. 2009; Kirono et al. 2012) and in the region (e.g. Jones et al. 2001) are sensitive to climate variables and climate change.

However, a similar process of salinization could occur in Lake Purrumbete over tens or hundreds of years following a change in climate. Under climate change, the local and regional groundwater systems would change, in particular due to changes in recharge rates across the landscape. Under a warmer, drier climate, this would mean less recharge and more saline recharge waters. There can be significant lags before these effects would be fully felt by the lake, especially for the salt balance. Therefore, assessing groundwater impacts using the method employed

in this study, which allows varying the groundwater inflow and outflow seasonally, is highly desirable. Often, groundwater fluxes are assumed to be constant in many lake–groundwater interaction assessments, which is unrealistic and would impact on the estimation of future water and salt balances for the lake. Based on the study at the nearby groundwater-fed Blue Lake, Dillon (1988) estimated that it would take hundreds of years for a new equilibrium nitrate concentration in groundwater to be reached from the time agriculture was initiated in the region.

Detailed modelling of the hydrology of the other freshwater lakes should be able to indicate if any of these currently fresh lakes have moved or are likely to move into a drying phase. If so, it would be worthwhile exploring options for enhancing their water supply or protecting them from overexploitation. As freshwater resources become scarcer, the remaining freshwater lakes will come under increasing consumptive and recreational pressures. The results of this study can be used to develop management strategies for Lake Purrumbete (and similar lakes elsewhere), to maintain surface water resources and water quality under the likely decrease in effective precipitation predicted by climate change scenarios for this region. Because Lake Purrumbete was relatively unaffected by the 1997–2010 drought, when many other lakes in this area became more saline and/or dried out, it served as an important refuge for aquatic ecosystem preservation, and this will also be the case if climate change causes seasonal drying of lakes to be a frequent occurrence by the end of the twenty-first century (Leahy et al. 2010). However, Lake Purrumbete is susceptible to fluctuations in nutrient concentrations due to the impact of surface warming on algal dynamics (Tibby and Tiller 2007), so its biodiversity could still be impacted. Lake Purrumbete is popular for trout fishing and also needs to be managed to maintain its amenity for this recreational activity.

The character of many lakes in the region has changed and the trend is likely to continue with impacts of climate change, which warrants a reassessment of conservation strategies and management of the lakes. Previous investigations in the region have also highlighted that the lakes' water quality (Tibby and Tiller 2007; Tibby et al. 2012) and levels (Jones et al. 2001) are more strongly influenced by changes in the climate rather than land use. The 1997–2010 drought had a greater impact on the shallow lakes (such as Lake Corangamite; Fig. 2) in the region than a major water diversion (Williams 1995; Timms 2005).

An extremely large salinity range was recorded in the lakes from the region, from freshwater Lake Purrumbete (<2000 mg/l), to a number of hypersaline lakes (Leahy et al. 2010). The formerly brackish salinity of many of the lakes across the region sustained important commercial and

recreational fisheries prior to the extreme increases in salinity, which now precludes the existence of all species of fish. The upper salinity tolerances for native fish are in the vicinity of 100,000 mg/l (Leahy et al. 2010). With many of the lakes becoming increasingly saline, the diversity of invertebrates and algae will fall. With so many of the lakes becoming increasingly saline or dry, it is imperative that those lakes and wetlands that remain freshwater, including Lake Purrumbete, or have the potential to be returned to a fresher state are given priority for conservation efforts and managed accordingly.

The observed changes in climate and lake conditions and projected changes in lake conditions require a management response. The findings of the study will inform adaptive management of Lake Purrumbete (and other high value lake systems) and may also have applicability to other lakes in the world. A similar lesson can be drawn from this study for freshwater bodies elsewhere across the globe.

The lake level drop will restrict the fringing wetland habitat; in a crater lake with steep slopes the changing shape of the shoreline will depend on the steepness of the slopes (e.g. as shown in cross section and plan view in Figs. 3, 5, respectively), to determine the extent of the lost wetlands under different scenarios. The current study showed that the lake level will drop by only a small amount, salinity will not be significantly affected and the most pressing matter is drying marshlands. The drying trend is placing added pressure on the scientific and environmental qualities of the lake. The lowering in lake level could cause a shift in the abundance of algal plankton and so influence the whole food web. This may reduce the invertebrate diversity of the lake. This suggests that a regional plan to manage the quantity and quality of Lake Purrumbete under a drying climate is needed. Therefore, the effects of lake level drops on the fringing habitat (how wide and where the lost habitats should be) and which changes, if any, could be induced on lake hydrology and ecology by the loss of these areas are among the key questions that can be addressed using this methodology, including if there is any significant threshold of water level drop, to trigger major ecological threats. The study will give insight into the potential changes to drivers of ecological communities resulting from climate change and their effect on water balance in deep fresh lakes in the world, such as Lake Purrumbete. This study considers the likely climate changes and their impacts to 2030, as this is considered a realistic timescale for management of the lakes.

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